



SLS

Space Launch System

Space Launch System Flight Control

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◆ Space Launch System (SLS)

- NASA-developed launch vehicle for large-scale (exploration-class) crew and cargo access
- Shuttle-derived hardware and processes leveraging Constellation program development experience (tanks, engines, boosters)
- Primary development configurations are 70t crew (SLS-10002) and 130t cargo (SLS-21002)

Vehicle	Booster	Core Stage	Upper Stage	Cargo
70t (10002) <i>Block I</i>	5 segment RSRMV	ET derived, 4x RS-25	ICPS, RL-10	MPCV (crew)
130t (21002) <i>Block II</i>	Advanced booster	ET derived, 4x RS-25	CPS, 2x J-2X	TBD

◆ Program schedule

- SRR/SDR Q2 FY12 *completed*
- PDR ~Q3 FY13
- CDR ~Q3 FY14
- Abort system tests ~Q4 FY15
- Exploration Mission (EM-1) (uncrewed, Block I) – ~Q1 FY18
- Exploration Mission (EM-2) (crewed, Block I) – ~Q1 FY22



◆ A new set of launch vehicle flight control design challenges

- Large, highly flexible vehicle structure with non-planar bending characteristics
- Complex TVC system with multiple fully actuated engines
- Massive propellant tanks with lightly damped lateral sloshing modes
- Uncertain payload envelope with parasitic dynamics (elastic, slosh)
- Highly optimized trajectories yielding widely varying operating conditions
- Aggressive robustness and redundancy requirements driven by human rating



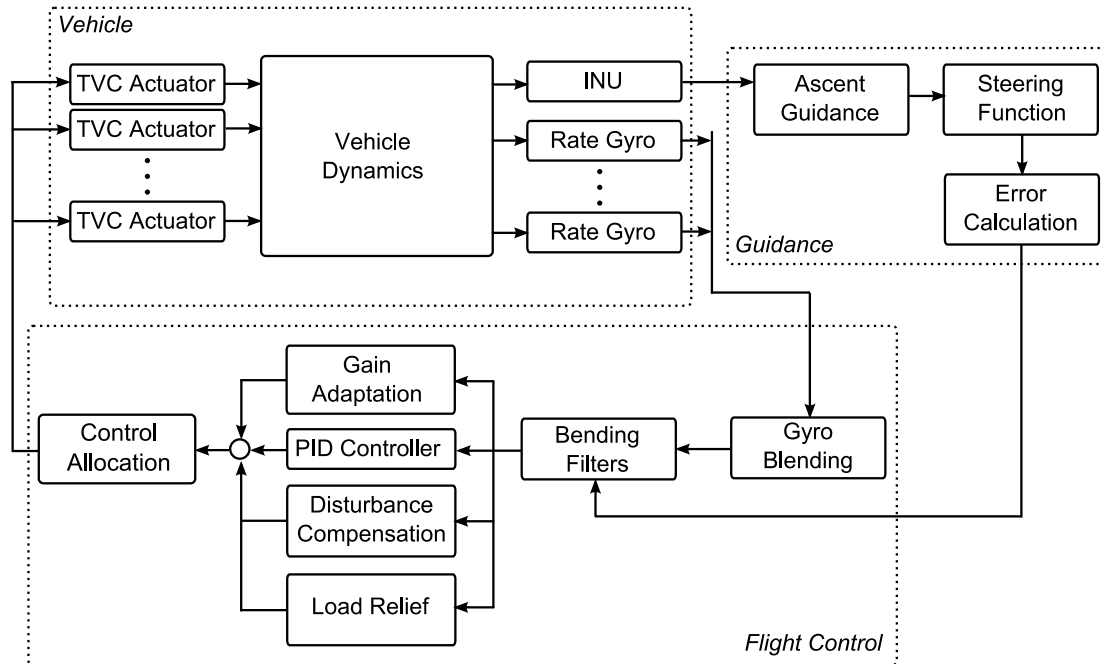
- ◆ **PID + linear bending filters is the architecture of choice**
 - Flight heritage, straightforward analysis, fundamentals understandable by non-controls engineers
- ◆ **Decoupled-axis duplicate pitch/yaw designs do not generalize**
 - MOI, control effectiveness varies with respect to body axis
 - Aerodynamic cross-coupling may be significant
- ◆ **Value added by augmenting PID/filters with a disturbance compensation algorithm**
 - Acceleration feedback (in some form) provides control over translational state of the system, which may be desirable for several reasons (load relief, drift reduction, lateral maneuvers, tower clearance)
 - Generalization of classical load relief (acceleration feedback) control
 - Includes a component that estimates bias angular accelerations
 - Better performance can be obtained than with integral control alone with respect to the same stability margin constraints

- ◆ **Use of multiple actuators necessitates an allocation algorithm**
 - Allocate actuator deflection to minimize some weighted figure of merit like total deflection (steering losses, control authority) or actuator rate (capabilities)
 - Can handle actuator failures based on external notification

- ◆ **Optimal allocation can be achieved with good accuracy based on combination of a *priori* data and flight-critical measurements**
 - Multiple phases, throttled engines
 - Control effectiveness is a function of time, propellant remaining, throttle, altitude, etc
 - Transport delay and actuator dynamics are variable with allocation
 - *Special feature of TVC & flex dynamics: mixing affects stability and loads!*

- ◆ **FCS design is more convenient in terms of angular acceleration than torque**
 - Eliminates some units and scaling issues in design of interacting parts
 - Well-conditioned matrix manipulations for control allocation

- ◆ **Rely on simple, proven, flight-tested algorithms and processes**
 - Classical PID control, gyro blending, linear bending filters, gain scheduling
 - Extensive frequency-domain and time-domain robustness
 - Algorithm and flight software commonality across all SLS platforms (common autopilot)
- ◆ **Enhance algorithm capability when warranted with compact and verifiable methods**
 - On-line optimal linear control allocation
 - High-performance acceleration based in-flight load relief capability
 - Model reference gain adaptation with spectral feedback
- ◆ **Maximize robustness to failures**
 - Tolerate at least one engine failure at any point in the flight regime with negligible impact to flight control performance
 - Demonstrate robustness to sensor failures and severe off-nominal conditions
- ◆ **Seamlessly integrate with the SLS Program to facilitate flight certification**
 - Shift toward TPM (Technical Performance Metric) reporting rather than classical stability margins and transient response characteristics only
 - Opens the design space and burdens the flight control designer (rather than systems engineering) with assessing the quality of the design at the lowest possible level



◆ **Integrated vehicle with control effectors and transducers**

- Vehicle controlled and parasitic dynamics (rigid body rotation and translation, propellant slosh, elasticity), hydraulic thrust vector control actuators, IMU + multiple rate gyros

◆ **Guidance algorithms**

- Open loop boost pitch program, Shuttle-derived linear tangent law (PEG) guidance, intelligent vehicle steering

◆ **Flight control algorithms**

1. Rate gyro blender
2. Bending filters
3. PID controller
4. Load relief and disturbance compensation
5. Gain adaptation law
6. Real-time fault-tolerant optimal control allocation (OCA) algorithm

◆ **Blending of multiple rate gyro signals is a well-known approach to mitigating excessive structural response**

- The positive and negative contributions of the modal elastic response at the sensor (mode slope or spatial shape function derivative) can be made to cancel at some nonzero positive weighting
- This is an optimal zero placement problem
- Practical blending must be robust to uncertainty in the structural dynamics
- Location of sensors is a design variable
- Numerical optimization is used to maximize robustness and preserve phase shape for certain modes (e.g. phase stable modes)

Design optimization methodology

Minimize

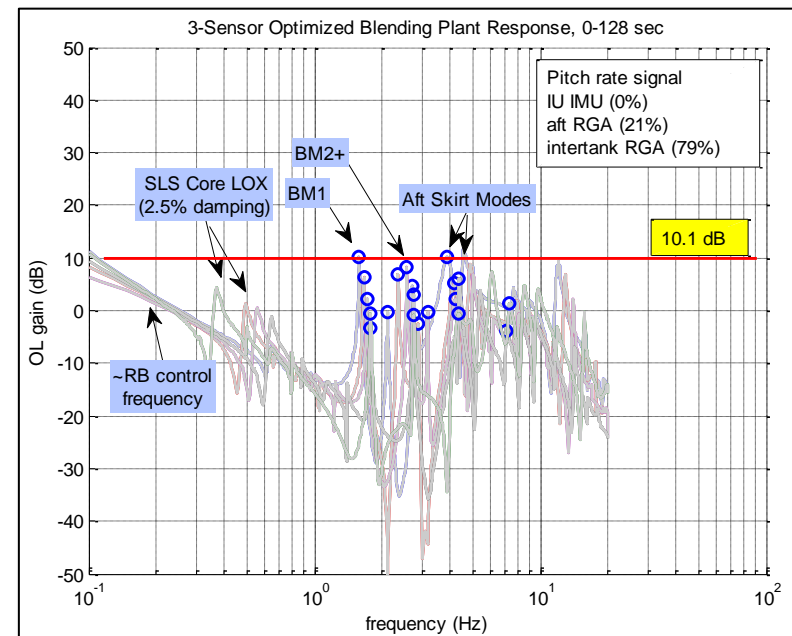
$$J(\alpha) = \sum_{t_k} \sup_{\omega} \left\{ \left| k_d^k \sum_{i=1}^q \alpha_i H_{\text{rat},i}^k(j\omega) + k_p^k H_{\text{att}}^k(j\omega) \right| \right\}$$

subject to

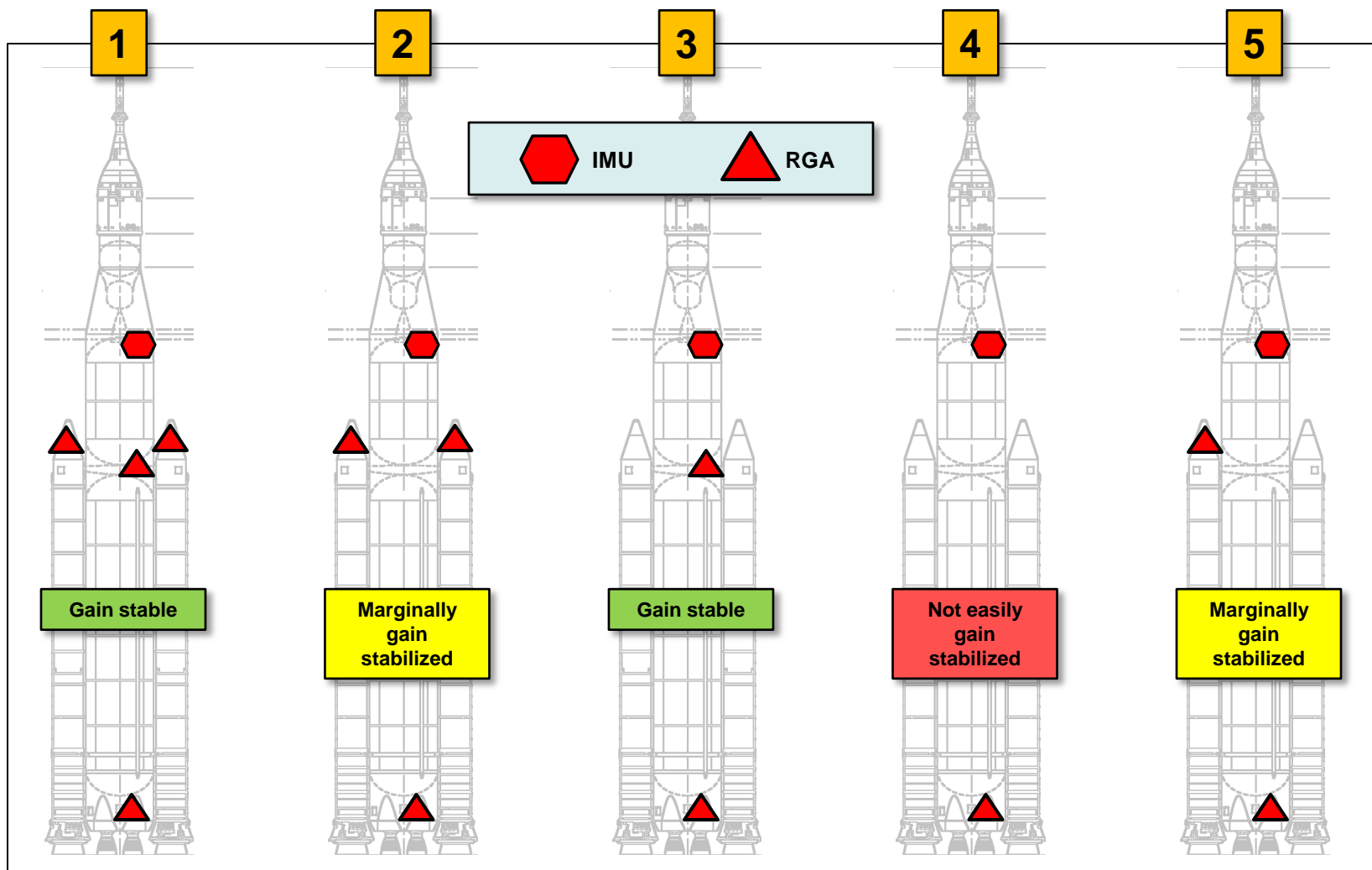
$$0 \leq \alpha_i \leq 1$$

$$\sum_{i=1}^q \alpha_i = 1$$

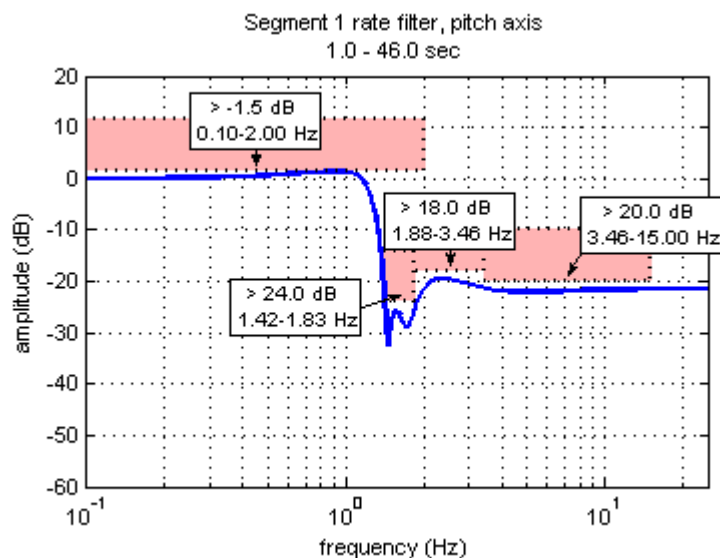
where k is the number of model times, q is the number of sensors, and $\alpha \in \mathbb{R}^q$.



- ◆ Various RGA locations considered to maximize robustness
- ◆ Configuration 2 POD (Shuttle derived), configuration 3 baselined



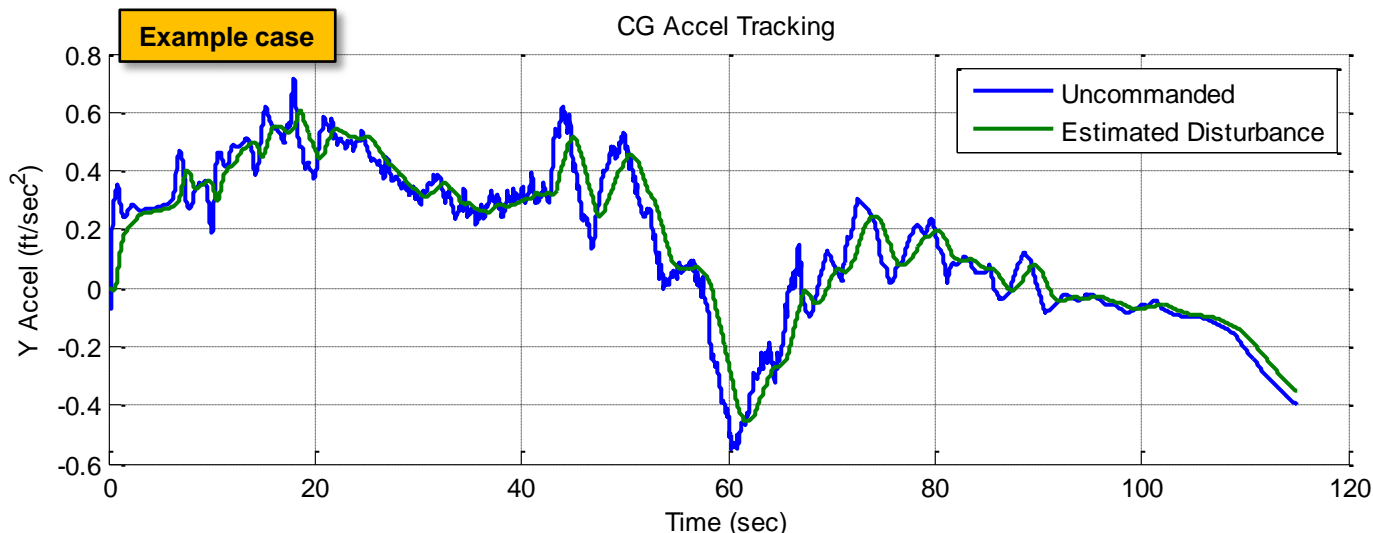
- ◆ Autopilot bending filter design usually assumes 0.5%-1.0% structural damping for design
- ◆ Test data indicates lateral bending mode damping consistent with this assumption
- ◆ Ares I design: 0.5% (not dispersed)
- ◆ Ares I-X design: 1.0% (dispersed $\pm 0.5\%$)
 - Tested at $\sim 0.2\%$ in VAB prior to flight
- ◆ Filters are designed to either phase-stabilize or attenuate flexibility with sufficient margin (~ 6 -10 dB)



Vehicle	Closed-loop rigid-body frequency (Hz)	Vibration mode	Frequency* (Hz)	Damping† ratio
Atlas/Able-4B	0.40	First Second Third	2.7 6.3 12.7	
Atlas/Agenda/OAO	0.40	First Second Third Fourth Fifth	3.6 7.2 8.2 9.5 15.0	0.007 — 0.016 0.012 0.012
Atlas/Centaur/ Surveyor	0.42	First Second Third	2.0 5.2 6.9	0.019 0.013 0.019
Thor/Delta or Agenda	0.20	First Fourth	2.2 17.0	0.007 0.010
Titan III-C Stage 0	0.25	First Second Third Fourth	1.8 2.9 5.4 >6.5	0.008 0.010 0.010 0.015
Upgraded Saturn I (SAD-6) (dynamic test vehicle)		First Second Third Fourth Fifth Sixth	1.7 3.3 4.1 5.0 5.6 7.2	0.008 0.009 0.014 0.008 0.006 0.007
Upgraded Saturn I (AS-205)	0.15	First Second Third Fourth Fifth Sixth	1.1 2.2 3.8 5.8 8.4 10.0	0.005 0.005 0.005 0.005 0.005 0.005
Saturn V/Apollo	0.20	First Second Third Fourth	1.0 1.7 2.3 3.0	0.005 0.007 0.006 0.010

- ◆ **IFLR has been generalized into angular/translational state observers**
 - The algorithms are in essence smooth differentiators.
 - We take quantities we know (commanded angular and lateral acceleration, angular rates) ...and estimate quantities we don't know and can't measure
 - The concept of disturbance estimation and compensation is not new for launch vehicles – similar (linear) implementations were used on Ares, Shuttle, etc.
- ◆ **Translational DCA example: for LR feedback, we want \ddot{r}_B , the acceleration at the CG**
 - The sensed acceleration, \ddot{r}_S , neglecting high-order and elastic effects, is given by

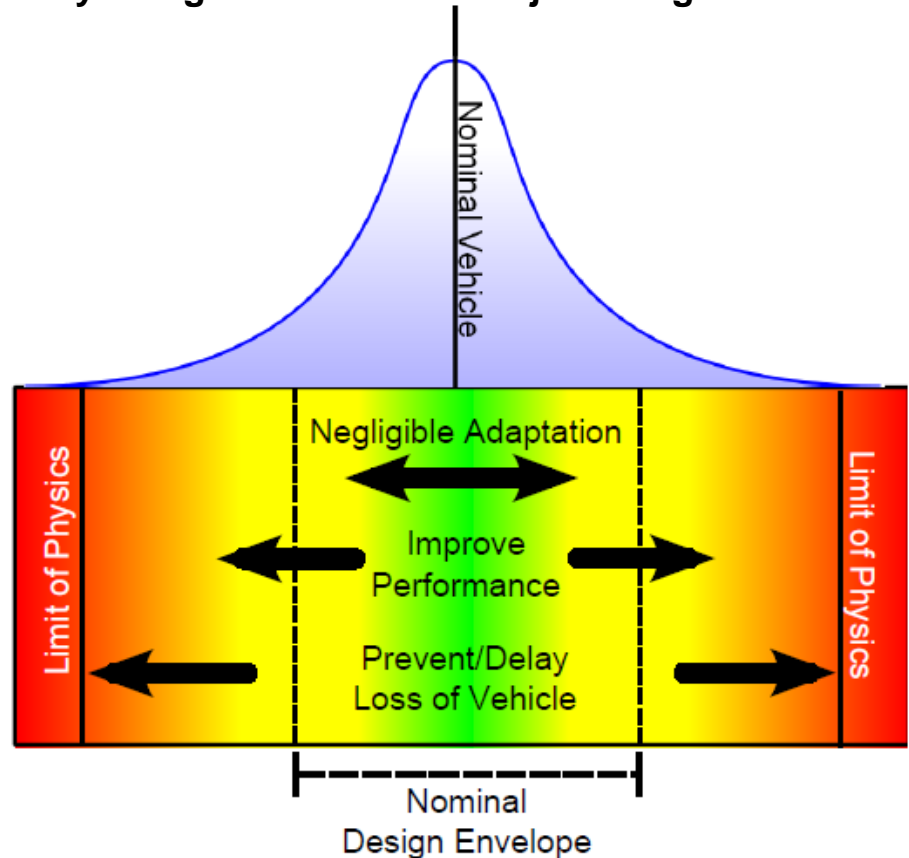
$$\ddot{r}_S = \ddot{r}_B + \dot{\omega}^\times r_{BS} + \omega^\times \omega^\times r_{BS}$$
 - We want to extract the body acceleration. We can subtract the last term, but the second term requires a measurement of $\dot{\omega}$ which we do not have.
 - A nonlinear observer is used to estimate $\dot{\omega}$ from ω , and extract the CG acceleration:



- ◆ In the absence of vehicle or environmental uncertainty, a fixed-gain controller is optimized prior to flight (no motivation for adaptation)
 - Conservatism in launch vehicle design generally yields well-performing classical controllers
 - There is no desire to improve on the well-tuned baseline control system design for nominal cases
- ◆ Adaptive control provides additional robustness by using sensed data to adjust the gain on-line

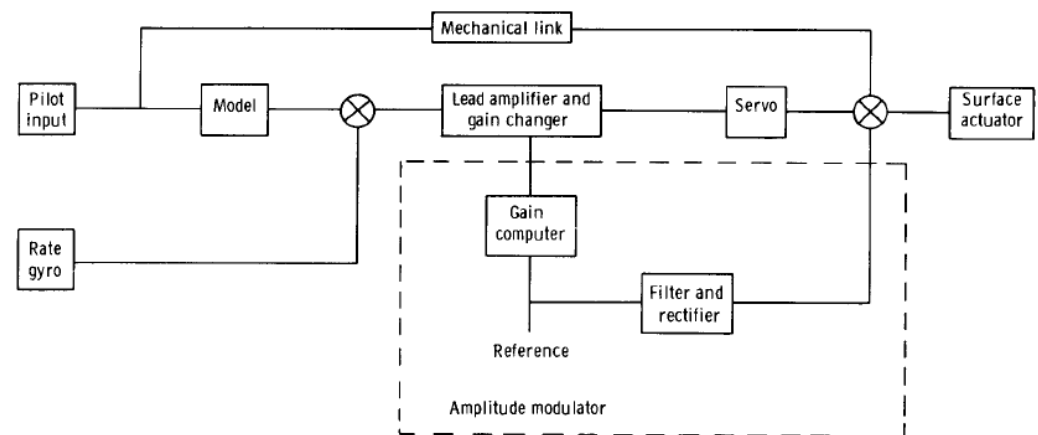
AAC Objectives

- “Do no harm”
 - Maintain consistency with classical design approach
 - Protect nominal control gains
- Increase robustness; prevent / delay loss of vehicle (LOV)

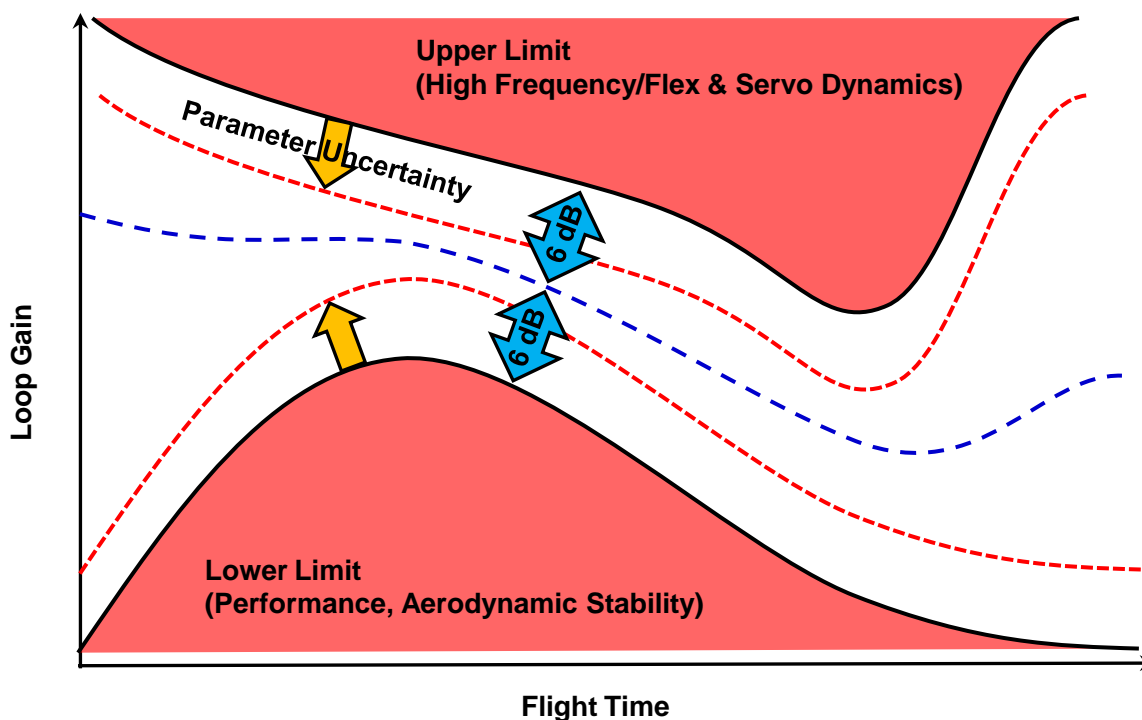


◆ **Current architecture has heritage to flight-tested systems**

- MH-90 (F-101) and MH-96 (X-20, X-15), ca. 1958-1967
- Based on a prescribed servo limit cycle amplitude (marginal servo poles)
- Saw numerous flight tests (>60) on X-15-3, improved performance and pilot opinion of handling qualities over wide-ranging flight envelope
- A similar concept is well-suited to a digital implementation



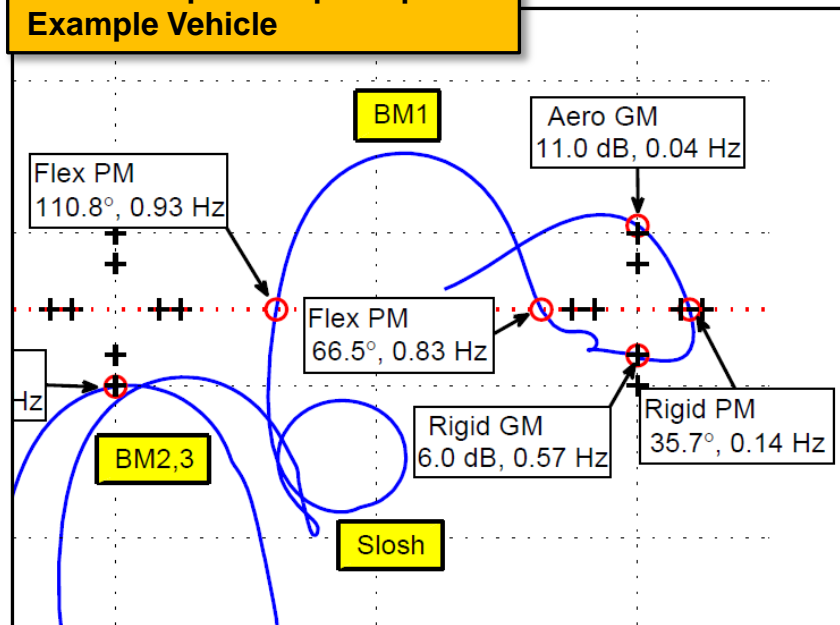
- ◆ Launch vehicles are often conditionally stable due to competing objectives of *unstable aerodynamics* and *parasitic internal dynamics*
- ◆ Because of uncertainty in models, we have to design with sufficient *gain margins*



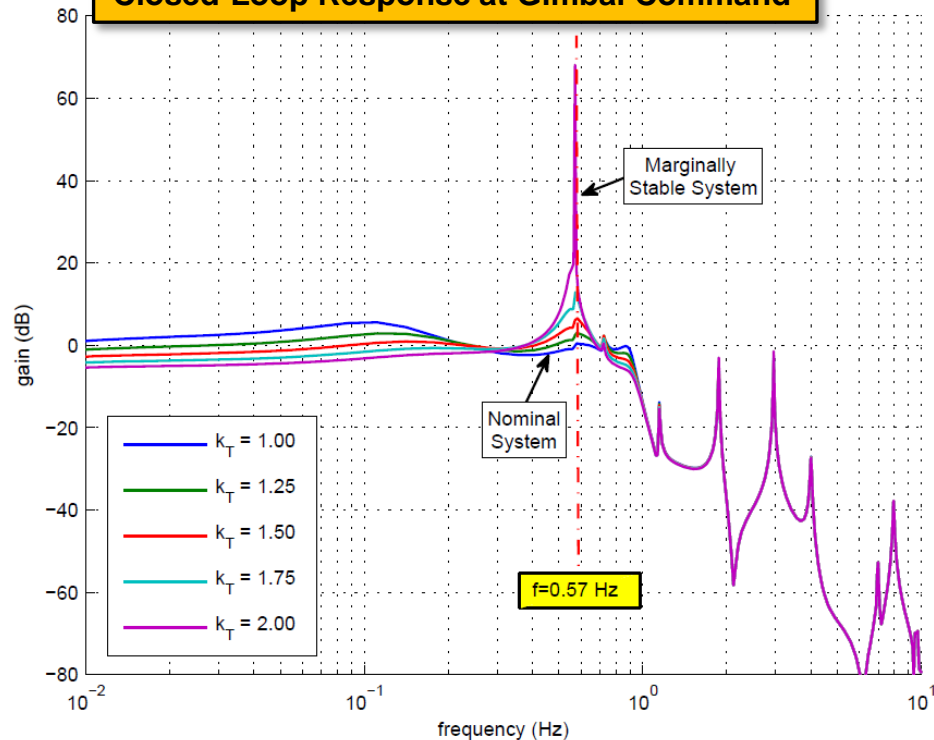
- ◆ *Adaptive gain augmentation senses off-nominal upper and lower limits in real time*

- ◆ **High-frequency closed-loop spectrum under high forward loop gain can be readily deduced from the open-loop frequency response**
 - Correlation allows design of spectral damper filters
 - Used directly to determine high-pass cutoff frequency specification

**Nominal Open-Loop Response
Example Vehicle**



Closed-Loop Response at Gimbal Command

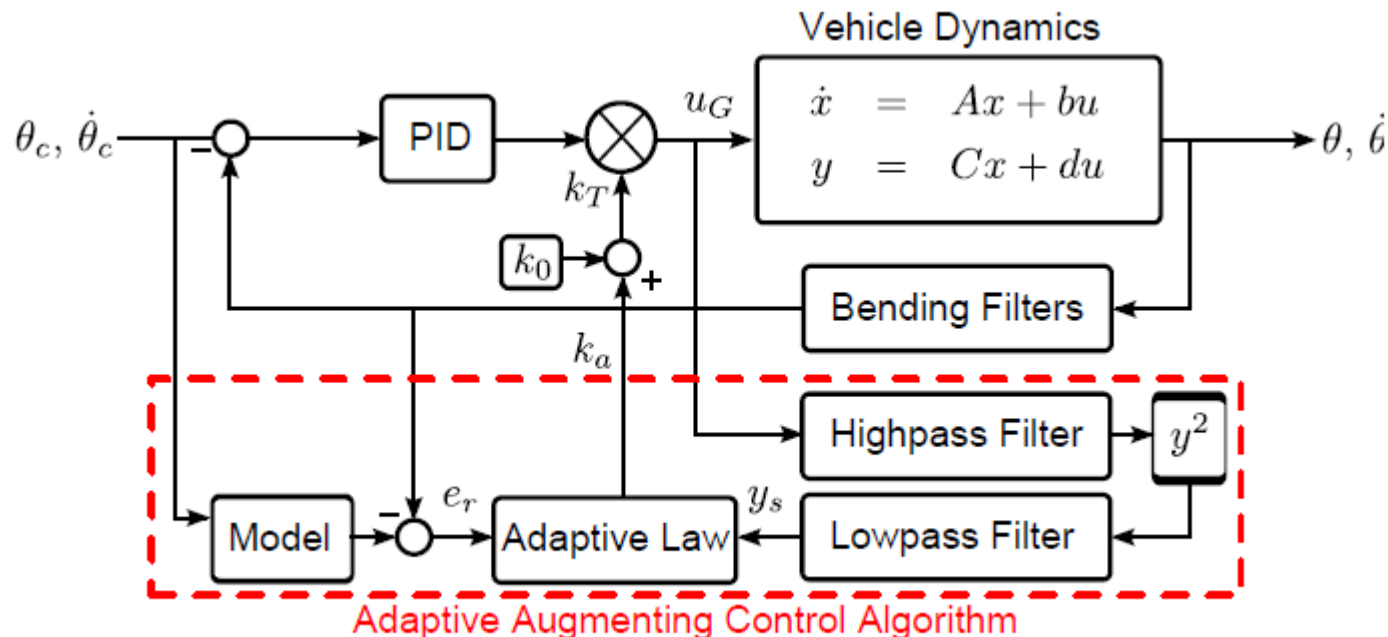


- ◆ Assume a well-tuned classical controller for the nominal system

- The forward loop gain k_T is augmented by a signal k_a
 - The total gain is formed from a fixed minimum gain and the augmenting gain;

$$k_T = k_0 + k_a$$

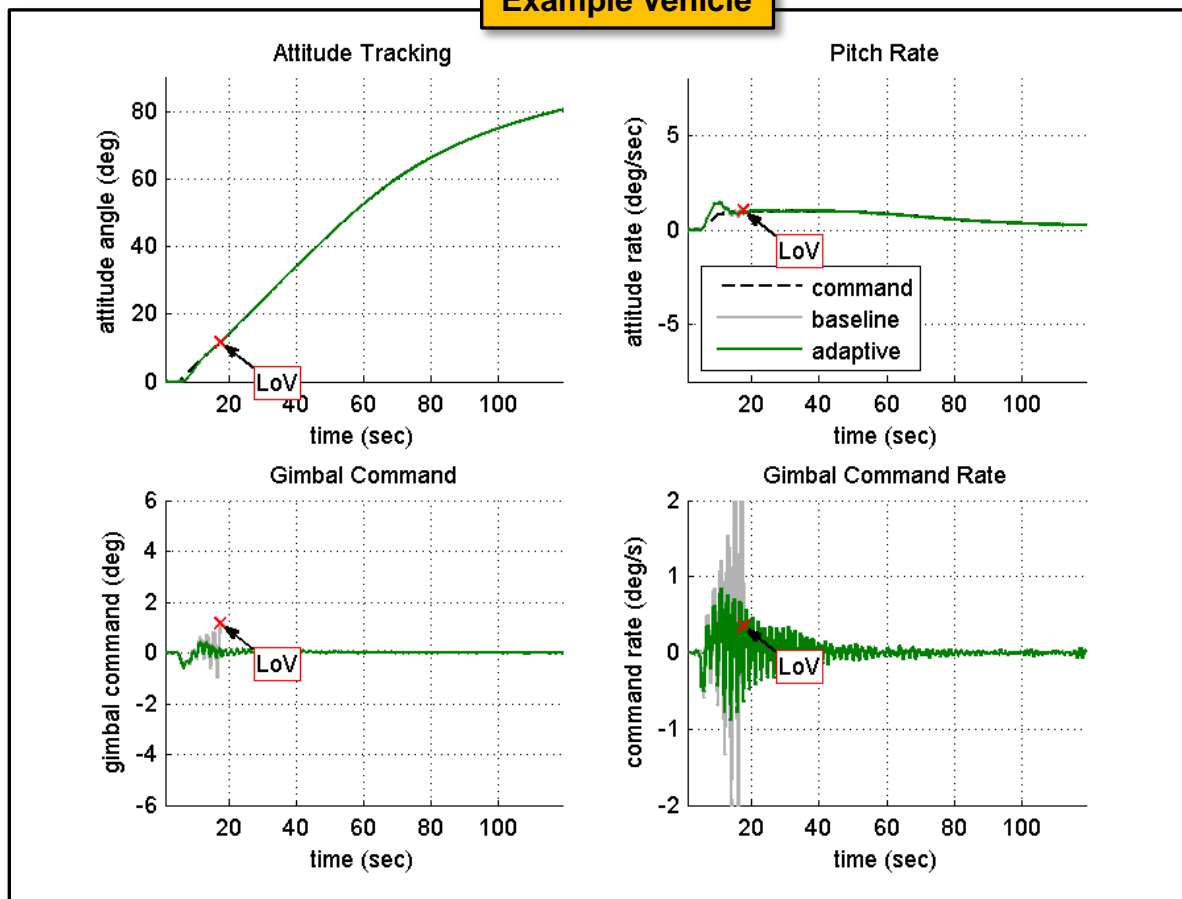
- Multiplicative augmentation is easy to assess in terms of gain margin
- The update law for the augmenting signal depends on the command, sensed attitude and rate, and the baseline controller output



◆ **Baseline controller induces structural resonance**

- Bending parameters are well-outside 3-sigma bounds for robust design
- Adaptive controller reduces gain to bring bending to stable limit cycle
- System slowly recovers lost performance as BM1 shifts up in frequency during flight

Example Vehicle



- ◆ **Multi-actuated thrust vector controlled systems are well-posed for control allocation**
 - Redundant control authority in three axes with two or more nozzles
 - Some configurations may have nine or more nozzles, each with two degrees of freedom

- ◆ **Solutions to the constrained allocation problem exist and can be implemented online**
 - In the face of constraints, we must solve an LQ or LP using an iterative algorithm
 - May not yield a moment collinear with command
 - Other constrained solutions include daisy chaining, etc.
 - A nonlinear solution: does not directly admit linear stability analysis

- ◆ **The constrained thrust vector control allocation problem differs from the aircraft problem**
 - Each control input has two degrees of freedom
 - Saturation constraints are insufficient to represent the constraint boundary. Coupled constraints apply to **two** degrees of freedom each
 - Due to significant servoelastic coupling, the **choice of effector mixing** at a given flight condition **affects the stability of the closed-loop structural-dynamic system**
 - **Linear allocators** are preferred to enable **linear stability analysis** of the short period dynamics for flight certification
 - **A linear allocator can be computed online** based on optimal parameterization (e.g., a weighting matrix)

◆ On-line Optimization

- LQ/LP
- Must consider convergence, stability analysis, computational expense

◆ Generalized Inverse Matrix Lookup

- Interpolation of matrix do not give exact results
- Requires substantial data storage for sufficient resolution

◆ Fixed polarity allocator with Vehicle/Engine Properties Scaling

- Shuttle-like approach
- Does not maximize the attainable moment
- Can adjust to guidance throttling

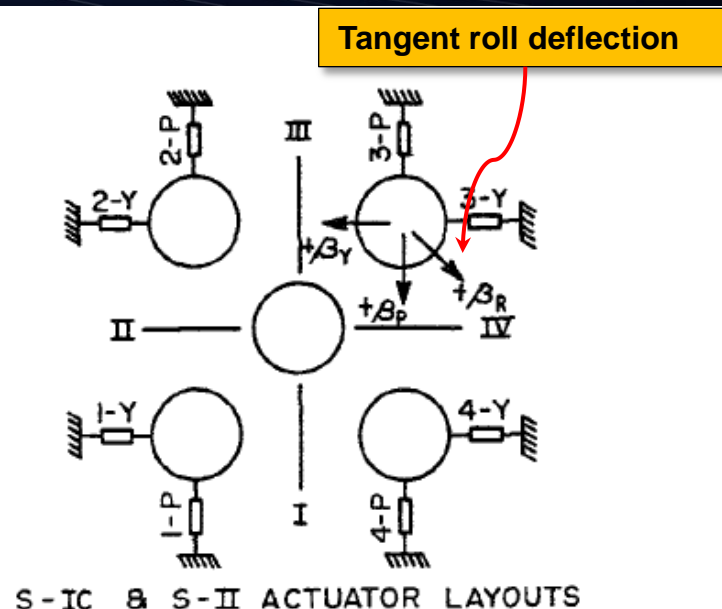
◆ Fixed Allocator (Polarity Matrix)

- Gains contain engine & vehicle properties
- Does not maximize the attainable moment
- Steering loss & local thrust structure loads

◆ Weighted Least Squares Cyclic Computation

- The best solution for launch vehicle application
- Reconfigurable In-flight to anomalies for which the system is prepared (engine out)
- Can adjust to guidance throttling
- Can maintain high allocation efficiency for many geometries

- ◆ Saturn vehicles used a polarity table that approximated the least-squares solution
- ◆ The push-pull arrangement of the actuators allowed nozzle motion tangent to the radius vector to the CM in the case of a roll command
- ◆ Least-squares allocators usually effect tangent motion to the virtual radius vector in the angular acceleration frame
- ◆ In body frame with a symmetric vehicle, circular constraints, and equal thrust engines, this behavior is almost optimal



S-IC & S-II POLARITY TABLE					
ACTUATOR NO.	SIGNAL & ACTUATOR MOVEMENT				
	$+\phi_R$	$+\phi_Y$	$+\phi_P$	$+\ddot{\gamma}_Y$	$+\ddot{\gamma}_P$
1 - Y	RET	RET		RET	
1 - P	EXT		RET		RET
2 - Y	EXT	RET		RET	
2 - P	RET		EXT		EXT
3 - Y	RET	EXT		EXT	
3 - P	EXT		EXT		EXT
4 - Y	EXT	EXT		EXT	
4 - P	RET		RET		RET

-roll

-yaw

pitch

-

+yacc

-zacc

- ◆ We compute a moment effectiveness matrix as a function of time

$$M = \begin{bmatrix} -F_1 r_1^\times u_1^\times & -F_2 r_2^\times u_2^\times & \dots & -F_k r_k^\times u_k^\times \end{bmatrix} \begin{bmatrix} T^{BG} \end{bmatrix}$$

- ◆ In terms of angular acceleration, it becomes

$$B = \begin{bmatrix} B_1 & B_2 & \dots & B_k \end{bmatrix}$$

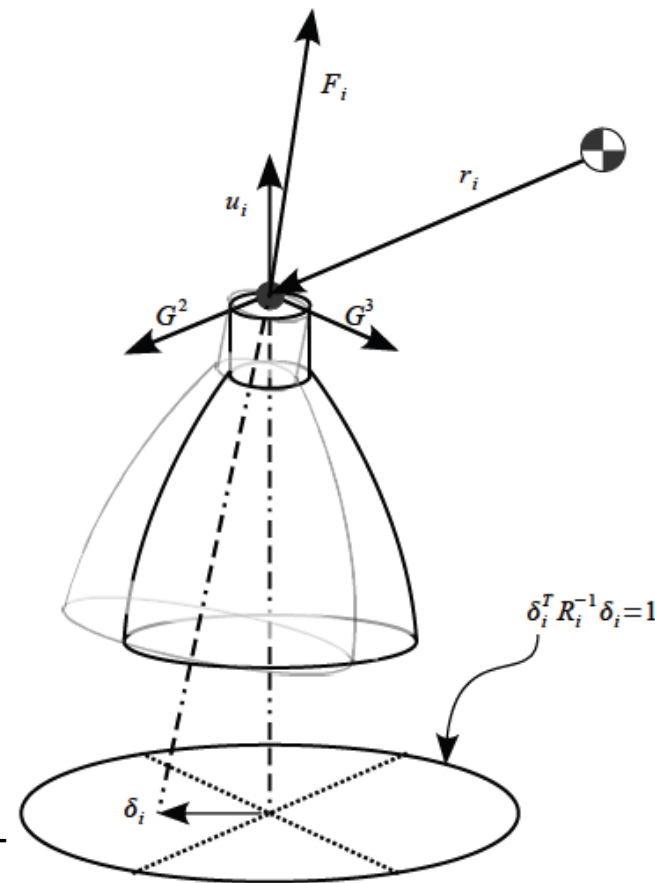
- ◆ We minimize $H = \frac{1}{2} \Delta^T R \Delta + \lambda^T (\dot{\omega}_c - B \Delta)$

with $\Delta = \begin{bmatrix} \delta_1^T & \delta_2^T & \dots & \delta_k^T \end{bmatrix}^T$

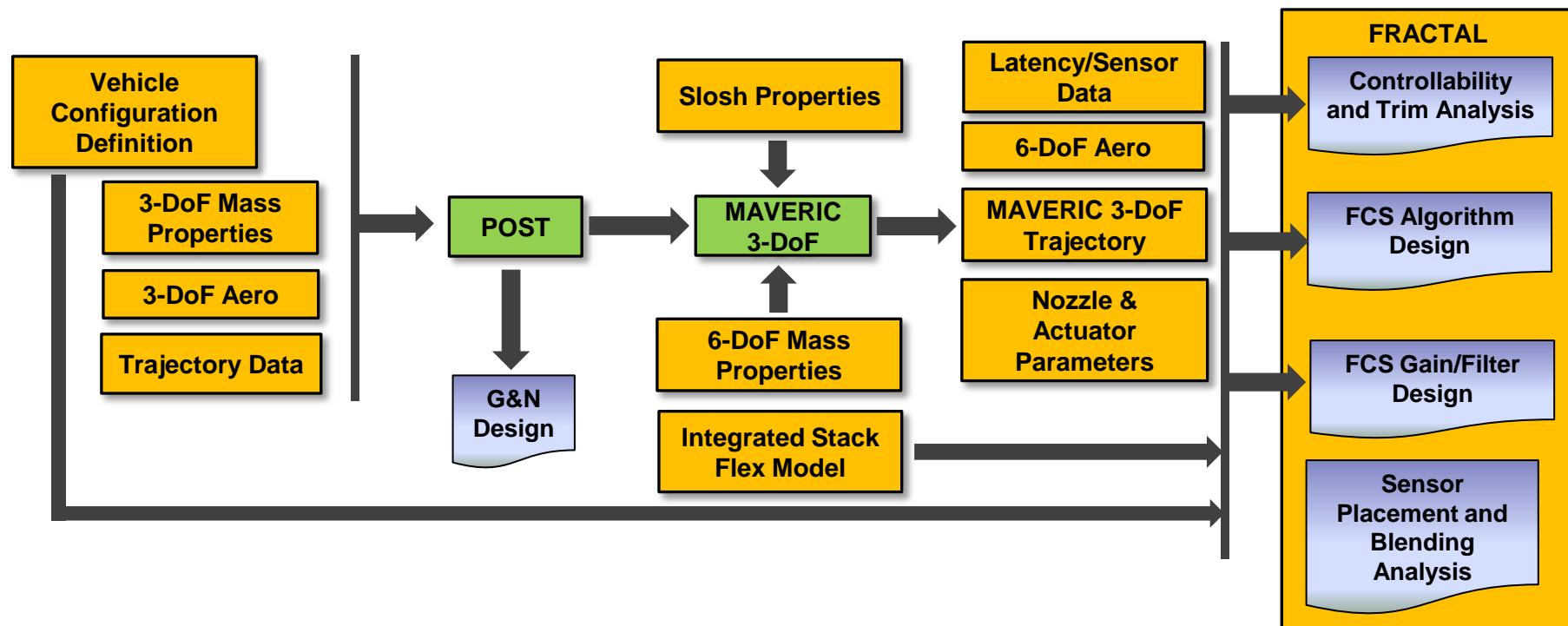
- ◆ Yielding the standard (WLS) structured generalized inverse

$$P(W) = W B^T (B W B^T)^{-1}$$

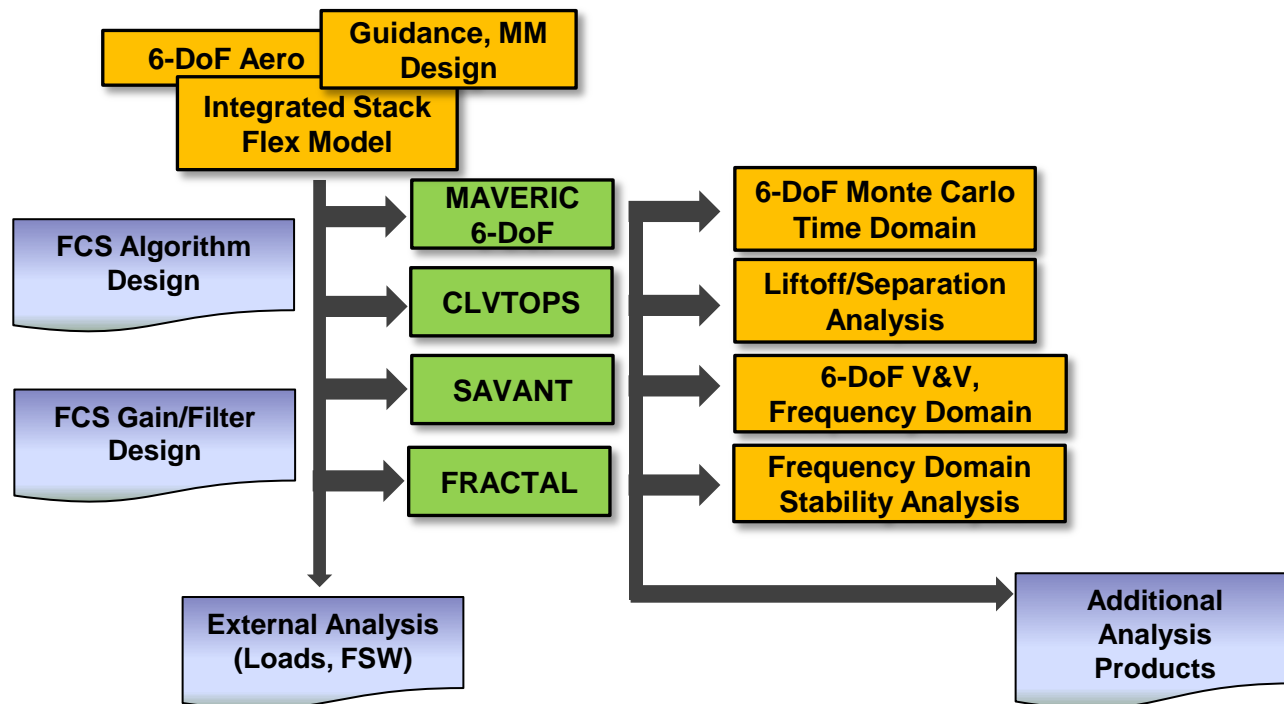
- The weight matrix can be determined online based on knowledge of the constraint boundaries and control effectiveness, such as engine out and guidance throttling.
- The problem can be expressed in a coordinate system where the matrix computations are sparse; scalar math can be used for high-efficiency computation
- Constraints can be satisfied using special features of the ellipsoidal topology of the constraint boundaries



- ◆ **POST [Program for Optimizing Simulated Trajectories] (LaRC / MSFC)**
 - 3-DoF trajectory optimization, guidance design, performance analysis
- ◆ **MAVERIC [Marshall Aerospace VEHICLE Representation in C] (MSFC)**
 - 3-DoF / 6-DoF flight mechanics simulation with high-fidelity elastic, slosh, actuator, atmospheric models
- ◆ **FRACTAL [Frequency Response Analysis and Comparison Tool Assuming Linearity] (MSFC)**
 - High-fidelity 6+-DoF perturbation analysis engine with parametric optimization capability



- ◆ **CLVTOPS** [*TREETOPS-derived*] (MSFC)
 - Multiple flexible body dynamic simulation, separation analysis, liftoff clearance analysis
- ◆ **SAVANT** [*Stability Aerospace Vehicle ANalysis Tool*] (MSFC)
 - 6+-DoF *Simulink*®-based flight mechanics simulation supporting numerical linear stability analysis
- ◆ **FRACTAL** [*Frequency Response Analysis and Comparison Tool Assuming Linearity*] (MSFC)
 - Large scale Monte Carlo frequency domain analysis



- ◆ **NASA and contractor teammates have developed a robust, scalable architecture for SLS flight control**
- ◆ **A careful balance of modern and heritage design principles maximizes performance and overall mission capability**

MSFC EV41 SLS Flight Control Team				
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